Potential Long-Term Benefits of No-Tillage and Organic Cropping Systems for Grain Production and Soil Improvement

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ABSTRACT

There have been few comparisons of the performance of no-tillage cropping systems vs. organic farming systems, particularly on erodible, droughty soils where reduced-tillage systems are recommended. In particular, there is skepticism whether organic farming can improve soils as well as conventional no-tillage systems because of the requirement for tillage associated with many organic farming operations. A 9-yr comparison of selected minimum-tillage strategies for grain production of corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], and wheat (*Triticum aestivum* L.) was conducted on a sloping, droughty site in Beltsville, MD, from 1994 to 2002. Four systems were compared: (i) a standard mid-Atlantic no-tillage system (NT) with recommended herbicide and N inputs, (ii) a cover crop-based no-tillage system (CC) including hairy vetch (*Vicia villosa* Roth) before corn, and rye (*Secale cereale* L.) before soybean, with reduced herbicide and N inputs, (iii) a no-tillage crownvetch (*Coronilla varia* L.) living mulch system (CV) with recommended herbicide and N inputs, and (iv) a chisel-plow based organic system (OR) with cover crops and manure for nutrients and postplanting cultivation for weed control. After 9 yr, competition with corn by weeds in OR and by the crownvetch living mulch in CV was unacceptable, particularly in dry years. On average, corn yields were 28 and 12% lower in OR and CV, respectively, than in the standard NT, whereas corn yields in CC and NT were similar. Despite the use of tillage, soil combustible C and N concentrations were higher at all depth intervals to 30 cm in OR compared with that in all other systems. A uniformity trial was conducted from 2003 to 2005 with corn grown according to the NT system on all plots. Yield of corn grown on plots with a 9-yr history of OR and CV were 18 and 19% higher, respectively, than those with a history of NT whereas there was no difference between corn yield of plots with a history of NT and CC. Three tests of N availability (corn yield loss in subplots with no N applied in 2003–2005, presidedress soil nitrate test, and corn ear leaf N) all confirmed that there was more N available to corn in OR and CV than in NT. These results suggest that OR can provide greater long-term soil benefits than conventional NT, despite the use of tillage in OR. However, these benefits may not be realized because of difficulty controlling weeds in OR.

No-tillage cropping systems have been shown to offer many benefits to soils and production of grain crops in the eastern USA (Grandy et al., 2006). After 28 yr of continuous tillage treatments in Ohio, the no-tillage system had higher organic C, cation-exchange capacity, hydraulic conductivity, aggregate diameter, and water-holding capacity than tillage systems (Mahboubi et al., 1993). On well-drained soils, corn and soybean yields were consistently higher with continuous no-tillage than conventional tillage (Dick et al., 1991). No-tillage systems were shown to reduce drought stress and increase yields of grain crops on upland soils in the piedmont of the southern states (Denton and Wagger, 1992). Corn root length density was higher in the top 0.1 m of soil under no-tillage than under conventional tillage, probably a result of higher water-holding capacity, capillary space, and proportion of water-stable aggregates in the surface soil (Ball-Coelho et al., 1998).

Many of the improvements to soils as a result of no-tillage production are related to increases in soil organic C which in turn relates to improvements in soil aggregation, water-holding capacity, and nutrient cycling (Weil and Magdoff, 2004; Grandy et al., 2006). Soil organic C can also be increased by other strategies, including addition of winter annual cover crops into rotations, diversifying rotations with perennial crops, addition of manure-based amendments, and organic farming, which often employs all of the preceding strategies. For example, soil organic C and N were increased by both reducing tillage and using winter annual cover crops, leading the authors to suggest that the best management system would include no-tillage and a mixture of legume and nonlegume winter annual cover crops (Sainju et al., 2002). Rotations that included at least 3 yr of perennial forage crops had the highest soil quality scores with total organic C being identified as the most sensitive quality indicator (Karlen et al., 2006). Manure- and legume-based organic farming systems from nine long-term experiments across the USA were shown to increase soil organic C and total N compared with conventional systems (Marriott and Wander, 2006). Crop yields and/or soil organic C was increased by organic vs. conventional cropping systems in the East (Pimentel et al., 2005), Midwest (Delate and Cambardella, 2004), and West (Clark et al., 1998).

Most comparisons of soil improvements in organic vs. conventional cropping systems have been conducted under conventional tillage conditions. The dilemma for organic farmers is that the approaches for increasing soil organic C usually require tillage. Specifically, tillage is required for eliminating perennial legumes before rotation to annual crops, for incorporating manure to avoid N volatilization losses, or for preparing a seedbed and controlling weeds. Since an increase in tillage intensity and frequency has been shown to decrease soil C and N (Franzluebbers et al., 1999; Grandy et al., 2006), increases in organic matter by utilization of organic materials in organic farming may be offset by decreases

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Abbreviations: CC, cover crop system; CV, crownvetch living mulch system; NT, no-tillage system; OR, organic system; SADP, Sustainable Agriculture Demonstration Project.

in organic matter from tillage. Some authors have speculated that conventional no-tillage agriculture may provide superior soil improvement and potential environmental benefits compared with organic farming because of the tillage requirement of organic farming (Trewavas, 2004). The need for long-term research has been advocated to assess the relative merits of conventional no-tillage agriculture compared with organic farming (Macilwain, 2004). There is little literature reporting such long-term comparisons. One 6-yr study in Pennsylvania showed that some form of primary tillage was required for crop yields in organic systems to match those in conventional systems, but that a pure no-tillage organic system was not viable (Drinkwater et al., 2000).

A long-term experiment, the Sustainable Agriculture Demonstration Project (SADP), was initiated at Beltsville, MD, to compare selected no-tillage grain cropping systems and a reduced-tillage organic system on a sloping, droughty site typical of the mid-Atlantic piedmont. The standard for comparison was a no-tillage system typical of that used in this area. Two additional no-tillage systems, one including winter annual cover crops and another including a perennial crownvetch living mulch, were compared with this standard for their potential to improve soil organic matter, reduce external inputs, and enhance environmental protection on erodible soils. Finally, an organic cropping system that reduced tillage to the minimum necessary for incorporation of manure and for weed control was included in this comparison. Performance of these systems during the first 4 yr of the experiment, which included transition years for the organic system, was reported by Teasdale et al. (2000). A simulation of projected yields, economic returns, and environmental impacts was reported by Watkins et al. (2002). This paper reports results from a comparison of these systems over a 9-yr period as well as a 3-yr uniformity trial that followed.

MATERIALS AND METHODS

Site Description

The SADP was established on a 6-ha site with 2 to 15% slope on the South Farm of the USDA-ARS Beltsville Agricultural Research Center in Beltsville, MD. On the basis of soil mapping of the site in 1994, five soils were identified: (i) coarse-loamy to loamy skeletal Typic Hapludult, (ii) coarse-loamy Typic Hapludult, (iii) fine-loamy Typic Hapludult, (iv) fine-loamy to coarse-loamy Aquic Hapludult, and (v) coarse-loamy to fine-loamy Aeric or Typic Endoaquult (M. Rabenhorst, 1995, personal communication). The field had been in a no-tillage corn–soybean rotation for at least 5 yr before plots were established.

Thirty-two plots that were 9.1 m wide and ranged from 120 to 170 m long were established on a contour across the slope of the field. Plots were separated by 1.8-m-wide grass strips. Rotations were initiated in fall of 1993 with establishment of wheat and cover crops. Four cropping systems were established, with each system initially following a 2-yr rotation with corn in the first year and wheat and/or soybean in the second year (Table 1). The intensive rotation with three crops produced in 2 yr (corn, wheat, and double-crop soybeans) is frequently practiced by growers in the mid-Atlantic region. On the basis of input from stakeholders in winter of 1998, changes were made to the crownvetch and organic rotations as described below.

The experimental design was a randomized complete block with four blocks. Each block contained eight plots so each of the four cropping systems was permanently assigned to a pair of plots. Plot pairs alternated annually between the corn and wheat/soybean phase of the rotation so that both rotational phases were present in every year for each cropping system. When a 3-yr rotation was instituted for the organic system in 1998, only two of the three phases of this rotation were present in a given year, resulting in no corn in 2000, no wheat in 1999 and 2002, and no soybeans in 1998 and 2001. Four transects were permanently established across the eight plots in each block such that soil type and topographical conditions were similar along each transect. These transects were used for sampling soil or plants as well as for establishing uniformity trial subplots (described below) so that influences of soil heterogeneity could be minimized as much as possible.

Details of system operations were presented in Teasdale et al. (2000). In brief, lime, P, and K were applied according to annual soil testing of each plot. The P and K were applied in inorganic form to the NT, CC, and CV systems, but in organic amendments to the OR system. Levels of soil pH, P, and K were maintained at levels suitable for crop production throughout the study according to University of Maryland recommendations. Corn and full-season soybeans were planted in early May, wheat in late October, and double-crop soybean in early July. Corn was planted with a no-tillage planter in 76-cm rows at an average population of 66,700 seed ha^{-1}. Organic soybeans were planted in 76-cm rows at an average population of 484,900 seed ha^{-1}. Soybeans in the nonorganic systems were planted in 38-cm rows until 1999 and were drilled in 19-cm rows thereafter at an average population of 498,600 seed ha^{-1}. Wheat was drilled in 19-cm rows at an average seeding rate of 130 kg ha^{-1} until 1999 and 223 kg ha^{-1} thereafter. Cultivars of

Table 1. Essential features of cropping systems at the Sustainable Agriculture Demonstration Project, Beltsville, MD.

	System			
Operation	**No-tillage**	**Cover crop**	**Crownvetch**	**Organic**
Rotation†	C–W/S	C–S	C–W/S, 1994–1997 C–W, 1998–2002	C–W/S, 1994–1997 C–S–W, 1998–2002
Cover crop	none	Hairy vetch before C, rye before S	crownvetch living mulch	crimson clover before C, rye before S
Tillage	none	none	none	chisel-plow and disk‡
Nutrient source	fertilizer (full)	fertilizer (reduced N) + cover crop residue	fertilizer (full) + cover crop residue	manure + cover crop residue
Weed control	PRE herbicides + POST herbicides	cover crop residue + POST herbicides	PRE herbicides + POST herbicides	cover crop residue + cultivation

† C = corn, W = wheat, S = full-season soybean, W/S = wheat followed by double-crop soybean.
‡ Chisel plowing preceded wheat planting in all years, preceded corn and soybean until 1998, and preceded fall cover crop planting thereafter.

each crop varied from year to year, but the same cultivar was planted in all systems in a given year.

System Description

The four cropping systems are described in Tables 1 and 2. All systems were developed with the expectation that (i) at least one grain crop would be harvested in every year, (ii) crops would be rotated, (iii) soil would be covered with vegetation or residue during as much of the rotation as possible, and (iv) tillage would be minimized to the extent possible within each system.

The NT system utilized typical practices for no-tillage grain production in the mid-Atlantic states. The absence of tillage and presence of surface residue was expected to protect the soil against erosion. Fertilizer management and herbicide applications were made according to University of Maryland recommendations. Nitrogen applications to corn were split between 57 kg ha^{-1} preplant, 17 kg ha^{-1} with the planter, and 85 kg ha^{-1} sidedressed, on average. Nitrogen applications to wheat were split between 22 kg ha^{-1} preplant and 78 kg ha^{-1} in early spring, on average. Preemergence herbicides were applied to eliminate existing vegetation and prevent subsequent weed emergence based on expected weed populations (Table 2). Postemergence herbicides were applied when weeds escaped control according to a near zero-threshold philosophy.

The CV system followed similar practices as the NT system except that crops were grown in a perennial crownvetch living mulch. This living mulch was expected to further reduce erosion and herbicide runoff compared with desiccated residue in a no-tillage field (Hall et al., 1984). Crownvetch was drilled after wheat harvest in 1994 and 1995 and allowed to establish during the remainder of those years rather than growing double-crop soybeans. Similar levels of inorganic N were applied to corn and wheat as the NT system since maximum corn yields were shown to require full N rates despite N contributions from the crownvetch (Duiker and Hartwig, 2004). Herbicides (Table 2) were applied before planting each crop with the intention to defoliate, but not kill, the crownvetch living mulch (N.L. Hartwig, 1995–2000, personal communications). Since excess competition with corn was experienced, a more aggressive program including a low dose of glyphosate at corn planting was initiated in 2000. Because no recovery time was available in the original corn–wheat/soybean rotation, the double-crop soybean crop was dropped from the rotation in 1998 to allow time for crownvetch regrowth.

The CC system used the winter annual cover crops hairy vetch before corn and rye before soybean. There was insufficient time to plant hairy vetch following a wheat/soybean double crop; thus, a full-season soybean crop was grown between May and September to permit hairy vetch to be planted in early October. Crops were planted into cover crop residue without tillage. Cover crop residue has been shown to suppress early-season weed emergence; consequently, a weed management program was followed that eliminated preemergence herbicides and applied postemergence herbicides based on species of emerged weeds (Teasdale and Rosecrance, 2003). In addition, hairy vetch has been shown to have a high N content and reduce the N requirement for corn (Decker et al., 1994); consequently, the preplant fertilizer N application to corn was eliminated and N was only banded with the planter and sidedressed as in the no-till system. Annual fertilizer N application to corn averaged 17 kg ha^{-1} with the planter plus 85 kg ha^{-1} sidedressed while N content of vetch aboveground biomass averaged 112 kg ha^{-1}.

The OR system followed a 2-yr corn–wheat/soybean rotation through 1997. Beginning in 1998, this was expanded to a 3-yr corn–soybean–wheat rotation to provide a legume (soybean) before wheat, an earlier planting date for the crimson clover (*Trifolium incarnatum* L.) cover crop after wheat, and time after wheat to control late summer weeds and reduce weed seed inputs to the soil seedbank. This 3-yr rotation is typical of organic systems used in other long-term experiments (Pimentel et al., 2005; Marriott and Wander, 2006). Crimson clover was grown as a green manure crop for corn (aboveground biomass contained an average of 109 kg N ha^{-1}). It was planted by overseeding into double-crop soybeans at leaf-drop before 1998 and thereafter by drilling into a chisel plow/disk-

Table 2. Herbicide programs for the three nonorganic cropping systems at the Sustainable Agriculture Demonstration Project, Beltsville, MD.†

Crop and application	System: No-tillage	System: Crownvetch	System: Cover crop
Corn			
Preemergence	1.8 kg ha^{-1} atrazine + 2.2 kg ha^{-1} metolachlor + 0.53 kg ha^{-1} paraquat + 0.56 kg ha^{-1} 2,4-D	1.8 kg ha^{-1} atrazine + 2.2 kg ha^{-1} metolachlor plus 0.53 kg ha^{-1} paraquat (1995–1999) or 0.56 kg ha^{-1} glyphosate (2000–2002)	none (1994–1998) or 0.53 kg ha^{-1} paraquat (1999–2002)
Postemergence	0.28 kg ha^{-1} dicamba (4 of 9 yr)	35 g ha^{-1} nicosulfuron (3 of 8 yr)	0.28 kg ha^{-1} dicamba (every year) plus 35 g ha^{-1} nicosulfuron (5 of 9 yr)
Wheat			
Preemergence	none (1994–1998) or 0.53 kg ha^{-1} paraquat (1999–2002)	0.53 kg ha^{-1} paraquat	–
Postemergence	18 g ha^{-1} thifensulfuron	18 g ha^{-1} thifensulfuron	–
Soybean			
Preemergence	1.1 kg ha^{-1} linuron + 2.2 kg ha^{-1} metolachlor + 0.53 kg ha^{-1} paraquat (1994–1997)	1.1 kg ha^{-1} linuron + 2.2 kg ha^{-1} metolachlor + 0.53 kg ha^{-1} paraquat (1996–1997)	0.53 kg ha^{-1} paraquat
Postemergence	1.1 kg ha^{-1} glyphosate (1998–2002)	0.32 kg ha^{-1} sethoxydim‡	0.28 kg ha^{-1} acifluorfen + 0.32 kg ha^{-1} sethoxydim (1994–1995) or 1.1 kg ha^{-1} glyphosate (1996–2002)

† Acifluorfen, 5-[2-chloro-4-(trifluoromethyl)phenoxy]-2-nitrobenzoic acid; atrazine, *N*-ethyl-6-methoxy-*N*′-(1-methylethyl)-1,3,5-triazine-2,4-diamine; 2,4-D, (2,4-dichlorophenoxy)acetic acid; dicamba, 3,6-dichloro-2-methoxybenzoic acid; glyphosate, *N*-(phosphonomethyl)glycine; linuron, *N*′-(3,4-dichlorophenyl)-*N*-methoxy-*N*-methylurea; metolachlor, 2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide; nicosulfuron, 2-[[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]amino] sulfonyl]-*N*,*N*-dimethyl-3-pyridinecarboxamide; parqaquat, 1,1′-dimethyl-4,4′-bipyridinium ion; sethoxydim, 2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one; thifensulfuron, 3-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl] amino]sulfonyl]-2-thiophenecarboxylic acid.

‡ Sethoxydim was applied in late summer of 1994 and 1995 during establishment of crownvetch after wheat harvest, and 3 of 5 yr after wheat harvest in 1998 to 2002 when crownvetch was allowed to regenerate. Soybeans were only planted in 1996 and 1997.

tilled seedbed in September following wheat harvest. Cow manure was applied to maintain soil nutrient levels based on University of Maryland recommendations and estimated N credits for the crimson clover cover crop. In 1994 to 1997, dairy solids were applied to corn and wheat at the average rate of 24,000 and 23,000 kg ha^{-1} (containing 0.51% N), respectively, and chisel plowed just before planting. Thereafter, composted dairy solids were applied to corn at an average rate of 9300 kg ha^{-1} (containing 1.3% N) by chisel plowing just before crimson clover seeding in September. Beginning in 1998, fresh dairy manure was applied to wheat at an average rate of 68,000 L ha^{-1} (containing 4.4 g N L^{-1}) and chisel-plowed just before planting. Weeds were controlled in corn and soybeans until 1998 by chisel plow and disking before planting followed by rotary hoeing and sweep cultivation after planting. Beginning in 1999, corn and soybean were planted without tillage, crimson clover and rye were flail mowed, their residues were left on the soil surface to suppress weeds, and weeds emerging after crop establishment were cultivated with a high-residue cultivator.

Data Collection

Grain yield was determined by combine harvesting the middle eight rows of corn, five rows of 76-cm soybean, nine rows of 38-cm soybean, and 3.8 m of drilled soybean and wheat over the entire plot length and weighing harvested grain in a weigh wagon. Moisture content of grain was determined and yield adjusted to 15.5% for corn, 13.5% for wheat, and 13.0% for soybean. Remaining grain was harvested and wheat straw was baled from the entire plot area. Corn and soybean plant populations and wheat head density were determined at physiological maturity at sites where the four transects crossed each plot.

Percentage of soil area covered by vegetation was visually estimated at key times during the crop rotations. Vegetation cover by cover crops and winter vegetation was estimated in spring just before cover crop termination and corn and soybean planting operations. Vegetation cover by weeds was estimated at maturity (seed production) in corn and soybeans and after harvest of wheat. Estimates were conducted by dividing the length of each plot into four quadrants and visually estimating the total percentage of the middle 6 m of each quadrant that were covered by live vegetation other than the crop and then determining the species fraction of the total. In early spring, 7.5-cm-diam. soil cores were taken at 10 sites across the center of each plot for determining the weed seedbank. These samples were taken at depths of 0 to 10 and 10 to 20 cm in 1993 and 1994 and a portion of this soil archived in a −20°C freezer.

Soil was sampled with a 5-cm diam. corer at 16 sites within the center 6 m of each plot at depths of 0 to 7.5, 7.5 to 15, and 15 to 30 cm after summer crops were harvested in fall. Composite soil from each plot and depth was analyzed by the University of Maryland Soil Testing Lab for soil organic matter (loss on ignition), pH (1:1 water–soil slurry), and P, K, Ca, and Mg (Mehlich 3, Wolf and Beegle, 1995) for use in determining crop nutrient recommendations for the following season. Beginning in 1999, a portion of composite soil from each plot and depth was sent to Penn State Agricultural Analytical Services Lab to determine total C and total N by combustion using a Fisons (Milan, Italy) NA 1500 Elemental Analyzer (Bremmer, 1996; Nelson and Sommers, 1996). Archived soil seedbank samples were analyzed for total C and N by the Penn State Agricultural Analytical Services Lab in 2002.

Analysis of variance was performed with PROC MIXED (SAS v. 9.1, SAS Institute, Cary, NC) and mean separation using the PDIFF option of the LSMEANS statement at $P < 0.05$ when the F test was significant. The need for variance partitioning was determined by comparing the AIC, AICC, and BIC output values from PROC MIXED with and without partitioning. Partitioning was only required for the analysis of weed cover data.

Uniformity Trial

Operations for all cropping systems were terminated after crops were harvested in 2002. Plots were fallow over winter, and all vegetation including volunteer cover crops were destroyed with glyphosate in early spring to create uniform planting conditions across all plots. All plots were planted to corn in 2003 to 2005 with fertility and weed control managed according to the NT system (Tables 1 and 2). Two 9- by 9-m sections were established in each plot, one without fertilizer N but with herbicide and the other without herbicide but with N. Each minus-N section within a plot was established along one of the soil uniformity transects within that block and each minus-herbicide section was established along another transect within that block. These minus-N and minus-herbicide sections continued in the same location from 2003 to 2005. After corn emerged, subplots that were four rows wide and 6.1 m long were established where corn populations were uniform within the minus-N and minus-herbicide sections. Corresponding subplots were established in areas adjacent to each minus-N or minus-herbicide subplot where corn was grown with recommended N and herbicide practices. This provided within each plot a contrasting plus and minus N and plus and minus herbicide set of subplots, each established along a transect of uniform soil conditions within each block. This design allowed for relatively precise estimates of the 9-yr (1994 to 2002) cropping system historical effect on corn grown in 2003 to 2005.

In each subplot, corn population was determined after sidedressing N and grain yield was determined by hand harvesting the middle two rows at physiological maturity. Corn grain also was harvested from entire plots, except the minus-N and minus-herbicide sections by combine as described for the 1994 to 2002 period. Grain yield was adjusted for grain removed by hand-harvesting the plus-N and plus-herbicide subplots. A presidedress nitrate test (Bundy and Meisinger, 1994) was performed by taking soil samples to 30 cm before sidedressing from all plus- and minus-N subplots. Corn ear leaf N was determined at silking from all plus- and minus-N subplots. Weed cover ratings were conducted on all minus-herbicide subplots at weed maturity (all other subplots received herbicide and were kept weed-free by hand weeding if necessary). Analysis of variance was performed using PROC MIXED as described above.

RESULTS

Systems Comparison, 1994 to 2002

Corn grain yield in the NT system varied considerably on this sloping, droughty site from over 10 Mg ha^{-1} in 1994 and 1996 when rainfall was abundant and evenly distributed across the season to almost nil in 1999 and 2002 during extremely dry years (Table 3). Weed control was good in NT, leaving on average 6% weed cover by the end of the season, consisting mostly of patches of bermudagrass [*Cynodon dactylon* (L.) Pers.] and scattered triazine-resistant smooth pigweed (*Amaranthus hybridus* L.). Corn yield of the CC system was similar to

Table 3. Corn and wheat grain yield and soil area covered by weeds at maturity at the Sustainable Agriculture Demonstration Project, 1994–2002.†

System	1994	1995	1996	1997	1998	1999	2000	2001	2002	LS mean‡
Corn grain yield§					Mg ha^{-1}					
No-Tillage	11.19a	6.63a	10.46b	3.01ab	2.78a	–	8.22a	7.17a	–	7.07a
Cover crop	11.58a	6.21a	9.80b	3.88a	2.49a	–	7.25b	6.97a	–	6.88ab
Crownvetch	–	3.63b	12.18a	1.34b	0.97b	–	8.16a	6.67a	–	6.20b
Organic	9.25b	6.27a	5.87c	1.23b	2.19a	–	–	4.54b	–	5.10c
Weed cover in corn					%					
No-tillage	4b	2c	8b	2c	5b	15c	7c	5d	4b	6d
Cover crop	2b	2c	29a	3c	5b	2d	77a	26c	11b	18c
Crownvetch¶	–	75a	33a	23b	50a	90a	40b	58b	64a	54a
Organic	9a	18b	14b	78a	13b	62b	–	79a	73a	44b
Wheat grain yield					Mg ha^{-1}					
No-Tillage	1.98a	3.45a	3.66a	2.69b	2.54b	4.30a	2.96b	2.36b	4.07a	3.11b
Crownvetch	–	–	4.18a	3.81a	3.37a	3.77a	4.30a	3.49a	3.99a	3.86a
Organic	3.27a	4.02a	2.61b	1.73c	2.64b	–	2.25c	4.14a	–	3.07b

† Values within year followed by the same letter are not different at $P < 0.05$.
‡ Least square mean.
§ Extreme drought in 1999 and 2002 prevented corn grain production.
¶ Weed cover includes the crownvetch living mulch.

that of NT in all years except 2000 when a heavy infestation of escaped grass weeds reduced yield (Table 3). Since no residual herbicides were used in the CC system and there was a reliance on surface hairy vetch residue and postemergence herbicides to control weeds, annual grasses, particularly large crabgrass [*Digitaria sanguinalis* (L.) Scop.] and fall panicum (*Panicum dichotomiflorum* Michx.) tended to escape this system. There was >10% weed cover in 4 of 9 yr with a trend toward greater abundance of grass weeds in the last 3 yr of the experiment, suggesting that a change in herbicide program would be needed in future years. Although not available when this experiment began, a postemergence program based on glyphosate and glyphosate-resistant corn would have greatly improved the weed control program for this system.

Herbicide applications in the CV system were designed to suppress but not kill the perennial crownvetch cover crop. During 1995 to 1999, herbicide treatments did not adequately suppress crownvetch in corn (Table 3). Crownvetch regrew rapidly and reduced corn yield relative to the best system in 3 of these 4 yr. Only during 1996, a year with exceptionally good rainfall distribution, was CV the highest yielding system, perhaps because of additional N provided by crownvetch desiccated before planting. To provide additional suppression of the crownvetch, a low rate of glyphosate was applied preplant in 2000 to 2002 (Table 2). This successfully slowed regrowth of crownvetch and reduced early competition with corn, resulting in similar corn yields in CV and NT in those years (Table 3). This additional suppression, however, reduced overall crownvetch vigor and stands such that spring soil cover declined from 65% in 1998 to 29% in 2002.

Weed cover in corn in the OR system was higher than that in systems with the best weed control in 6 of 8 yr and corn yield was lower in 4 of 6 yr (Table 3). Weed control and corn yield in the OR system were best in the first year of the experiment but declined as the experiment progressed. During 1994 to 1998, weed control by preplant chisel-plowing followed by rotary hoeing and cultivating maintained weed cover at <20% in 4 of 5 yr. Corn yields were similar in the OR and NT in two of those years, 1995 and 1998. In the other 2 yr, 1994 and 1996, lower yields in the OR system may have been the result of inadequate fertility to achieve the high yield potential resulting from good rainfall in those years. Spring chisel plowing was eliminated from 1999 to 2002 with reliance on cover crop residue and between row cultivation with a high-residue cultivator for weed management. Drinkwater et al. (2000) reported good weed control and yields equivalent to a conventional no-tillage system using a reduced-tillage organic system for corn production similar to this. However, this system resulted in poor weed control in 1999 to 2002 (Table 3) and a shift from a mix of smooth pigweed, common lambsquarters (*Chenopodium album* L.), and annual grasses in early years to domination by annual grasses, predominately giant foxtail (*Setaria faberi* Herrm.), in later years.

There were few differences between systems in harvested corn populations (data not shown). However, stand was reduced in OR in 3 of the first 4 yr (the 1994–1997 population reduction in OR vs. NT averaged 27%) and this may have contributed to yield reductions in those years. Stand losses in OR were the result of an uneven seedbed left after chisel plowing and disking the crimson clover cover crop and resulting damage by rotary hoeing and cultivating. Employment of the no-till planting system beginning in 1999 resolved these population problems.

Similar results were obtained in soybeans as corn but comparisons between systems were confounded by differences in planting dates among systems (data not presented). Full-season soybeans grown in CC averaged 3.38 Mg ha^{-1}, whereas double-crop soybeans grown after wheat in NT averaged 2.02 Mg ha^{-1} across all years. Weed control was excellent in NT and CC soybeans in all years averaging <4% weed cover except for CC in 1994 and 1997, when morningglory (*Ipomoea* spp.) and annual grass weeds escaped to give ≈20% year-end cover. Double-crop soybeans were grown in OR until 1997 and had similar yields to those in NT (P = 0.416) with weed cover that averaged 21% in those

Table 4. Total soil combustible C and N averaged over 2001 and 2002 at the conclusion of the cropping systems comparison.

System	Soil depth, cm 0–7.5	7.5–15	15–30
Soil C		$g\ kg^{-1}$	
No-tillage	15.5c†	11.1c	7.1b
Cover crop	17.3b	12.4b	7.8b
Crownvetch	14.4c	11.1c	7.4b
Organic	19.2a	15.9a	10.3a
Soil N			
No-tillage	1.29c	0.93c	0.58b
Cover crop	1.43b	1.04b	0.64b
Crownvetch	1.22c	0.98bc	0.66b
Organic	1.59a	1.30a	0.87a

† Values within a depth range followed by the same letter are not different at $P < 0.05$.

years. Full-season OR soybeans were grown without chisel plowing and rotary hoeing after 1998, resulting in poorer weed control that left an average of 39% year-end weed cover. Yield comparisons during these years were limited because of drought that resulted in no yields in 1999 and 2002 and rotation out of soybeans in 1998 and 2001.

Wheat yield was higher in the CV system than the NT system in 4 of 7 yr (Table 3). Since the crownvetch living mulch grows primarily in summer months, competition from this perennial during the winter wheat production season from fall to spring was minimal. But, N released from killed crownvetch before planting wheat probably stimulated tiller production and growth of wheat relative to the NT system. Wheat yield in the OR system was lower than that in the other systems in 3 of 7 yr. Lower yields may have been the result of insufficient N mineralization from fall manure application during cold season months. Also, volunteer rye in OR wheat in 2000 may have contributed to the lower yield in that year. Weed growth was minor in OR wheat during the growing season but weeds did increase in abundance after wheat senescence. The pattern of wheat yield response to cropping systems was usually similar to the pattern of wheat head density in these systems at maturity (data not presented).

At the end of the experiment, total combustible soil C and N made up a higher fraction of soil dry weight in the OR system than all other systems at all depths (Table 4). Soil C and N concentration was higher in the CC system than the NT and CV systems at the shallower depths. Soil organic matter determined by loss-on-ignition showed a similar pattern of response to cropping systems as that of total soil C (data not presented). At the beginning of the experiment, soil C and N was not determined. However, soils archived for seedbank analysis in 1993 and 1994 provided a means to determine initial total C and N levels. These samples were not taken at the same depths as soil nutrient samples, so a direct comparison of initial and ending values is not possible. However, analysis of these samples showed no initial difference among cropping systems in total soil C ($P = 0.702$ and $P = 0.400$ at 0–10 cm and 10–20 cm, respectively) or total soil N ($P = 0.739$ and $P = 0.224$ at 0–10 cm and 10–20 cm, respectively). This data provides evidence that differences between systems in soil C and N observed at the end of this experiment represented changes that occurred as a consequence of these systems during the course of this experiment.

Uniformity Trial, 2003 to 2005

There was no interaction between system and year for corn yield and N variables across the 3 yr of this uniformity trial, so data averaged over years are shown (Table 5). Corn grown in whole plots in 2003 suffered from erratic populations following heavy rains during establishment in that year, thus only whole-plot yields for 2004 to 2005 are shown. Subplots were located on transects in better-drained areas of the field so uniform corn populations were obtained in all years and subplot data are presented across all three uniformity trial years. Yield of corn grown on plots with a 9-yr history of OR were 16 and 18% higher in the whole plots and subplots, respectively, than those with a history of NT (Table 5). Corn grain yield from plots with a history of crownvetch were 9% (not significantly different) and 19% higher in the whole plots and subplots, respectively, than those with a history of NT. There were no differences between corn yield of plots with a history of NT and CC in either the whole plots or subplots.

Three measures of N availability all confirmed that higher subplot grain yields of corn in the OR and CV than in the NT and CC systems could be explained by higher N availability (Table 5). First, the yield reduction in subplots with no applied N relative to adjacent N-treated subplots was lower in OR and CV than in NT. Second, a presidedress nitrate test in subplots without applied N showed higher soil nitrate in OR and

Table 5. Corn grain yield, soil nitrate N before sidedressing, and corn ear leaf N during the uniformity experiment 2003 to 2005 in response to the historical effects of cropping systems operational from 1994 to 2002.†

System from 1994–2002	Grain yield, whole plot 2004–2005	Grain yield, subplot‡ 2003–2005	Yield reduction without N§	Soil nitrate N in minus-N subplots	Corn ear leaf N
	$Mg\ ha^{-1}$		%	$mg\ kg^{-1}$	%
No-tillage	5.76b¶	6.51b	59.6a	14.8b	2.49b
Cover crop	5.84b	6.85b	52.6ab	18.8ab	2.52b
Crownvetch	6.25ab	7.75a	45.2b	20.2a	2.66a
Organic	6.70a	7.66a	43.1b	21.0a	2.69a

† Corn was produced in all plots during 2003 to 2005 according to the no-tillage system.
‡ Grain yield for subplots with fertilizer N and herbicide.
§ Yield reduction without N is the yield reduction in subplots without fertilizer N relative to paired subplots with fertilizer N.
¶ Values within columns followed by the same letter are not different at $P < 0.05$.

CV than in NT. Third, corn ear leaf N at silking was higher in OR and CV than in NT or CC.

In subplots with no herbicide application during 2003, weeds emerged earlier and more abundantly in the OR system, whereas the fewest weeds emerged and developed in the NT system (Table 6). As a result, yield reduction in the weedy subplots relative to the adjacent weed-free subplots was highest in the OR and lowest in the NT system in 2003. This result reflects the larger weed seedbank that probably had built up in the OR than the NT system over the preceding 9 yr. After 1 yr without herbicides, the seedbank apparently equilibrated in all subplots sufficiently so there were no differences in weed cover or yield reduction between systems in 2004 and 2005.

DISCUSSION

Growing an intensive 2-yr rotation of corn, wheat, and soybean without tillage with recommended fertilizer and herbicide inputs has been an efficient system for grain production in the mid-Atlantic states. Previous research that characterized these systems during the first 4 yr (Teasdale et al., 2000) demonstrated the NT system had the highest ratio of grain per total vegetation produced, because only grain crops were grown throughout the 2-yr rotation and potentially weedy vegetation was controlled. This previous research also showed that NT had a higher water-use efficiency than CV or OR, which can be attributed to the maintenance of high residue levels with few weeds. However, this system achieved these efficiencies at the expense of external chemical subsidies to maintain high nutrient levels and eliminate competition from unwanted vegetation. Simulation analysis of these systems (Watkins et al., 2002) predicted that the NT system would exceed limits for herbicide and nutrient contamination of surface and ground water in some years.

Winter annual cover crops can amplify many of the benefits of no-tillage cropping systems for protecting and improving soils. Cover crops offer several advantages for nutrient and water management (Decker et al., 1994; Clark et al., 1995). Previous research showed that the CC system had the highest grain production efficiency per unit N input and per soil water-use in this experiment (Teasdale et al., 2000). Higher vegetative residues (including more legumes) returned to soil in CC than in NT probably accounted for these higher N-use and water-use efficiencies (Teasdale et al., 2000) as well as the increase in soil C and N in CC vs. NT in the surface 15 cm of soil (Table 4). Seo et al. (2006) also showed that N from hairy vetch residue contributed about twice as much N to soil as did fertilizer N. However, overall soil conditions were not changed sufficiently in CC relative to NT to statistically affect corn yield in the uniformity trial following the systems trial (Table 5). Reliance on a postemergence herbicide program in CC also led to potentially minimal herbicide movement into ground and surface water (Watkins et al., 2002).

The CV system produced the highest average wheat yield and the highest corn yield in a year with exceptionally good moisture availability; however, competition between this perennial cover crop and corn led to excess competition for moisture when moisture was limiting. Previous research showed there was a reduction in water-use efficiency in CV compared with NT (Teasdale et al., 2000). Duiker and Hartwig (2004) also showed that crownvetch and other living mulch species reduced corn yields in dry years. Only when the herbicide program suppressed crownvetch to the point of stand depletion in the later years of this experiment was corn yield not affected. On the other hand, the CV system did provide long-term benefits to the soil as shown by increased subplot corn yield and greater N availability compared with NT during the uniformity years (Table 5). The CV system did not raise soil C and N concentrations during the 9 yr of this systems trail (Table 4), nor during a 10-yr period in a Pennsylvania trial (Duiker and Hartwig, 2004). Instead, increased N availability could be explained by development of the perennial crownvetch root system that opened new channels for subsequent corn roots to access N and water from deeper in the soil profile. Katsvairo et al. (2006) review the capacity of perennial grasses to increase the rooting depth of subsequent crops in rotation, particularly on shallow soils such as those at the SADP site.

The OR system resulted in lower average corn yield than the other systems and weed control declined as the experiment progressed (Table 3). Several factors contributed to poor weed control. First, chisel-tillage of crimson clover and manure led to an uneven seedbed and difficulty controlling early emerging weeds by rotary hoeing during the early years. Perron et al. (2001) also observed increased weed populations when chisel-plowing was combined with mechanical weed control because of surface residue interference with mechanical cultivation operations. Second, mowed cover crop residue used to suppress early weed emergence in later years was not sufficiently uniform to provide effective weed control (crimson clover averaged 74% soil coverage before mowing). Third, sweep cultivation controlled

Table 6. Weed cover and corn grain yield reduction by weeds during the uniformity experiment 2003 to 2005 in response to the historical effects of cropping systems operational from 1994 to 2002.†

System from 1994–2002	Weed cover in weedy subplots‡ 2003	Weed cover in weedy subplots‡ 2004–2005	Yield reduction with weeds§ 2003	Yield reduction with weeds§ 2004–2005
	%			
No-tillage	54c¶	87a	22.9c	49.9a
Cover crop	79b	88a	50.1b	54.3a
Crownvetch	83ab	84a	32.1bc	45.9a
Organic	93a	82a	87.4a	44.6a

† Corn was produced in all plots during 2003 to 2005 according to the no-tillage system.
‡ Percentage of soil area covered by weeds at weed maturity. Annual grasses were the dominant species except for a mix of grasses and smooth pigweed in the no-tillage system in 2003.
§ Percentage yield reduction with weeds is the yield reduction in subplots without herbicide relative to paired weed-free subplots with herbicide and hand weeding.
¶ Values within columns followed by the same letter are not different at $P < 0.05$.

weed seedlings with a lower efficiency in no-tillage systems because of inability to fully disrupt weed root systems within the relatively larger soil aggregates than those found in tilled soil (Teasdale and Rosecrance, 2003). Fourth, the short grain crop rotation used in this OR system was probably unsuitable for maintaining sufficiently low weed seedbank populations for an effective organic weed control system. Longer rotations that include a hay crop are more effective at maintaining lower weed seedbanks and improving weed control in organic systems (Teasdale et al., 2004). Inclusion of a perennial hay crop in this organic rotation may have improved weed control and also provided additional yield-improving benefits as those observed from the perennial crownvetch cover crop described above.

Despite poor weed control, the OR system improved soil productivity significantly as measured by corn yields in the uniformity trial (Table 5). Teasdale et al. (2000) showed that, across the complete rotation, the OR system returned approximately twice the organic dry matter from manure (19 Mg ha^{-1}) and vegetation (18 Mg ha^{-1}) to soil compared with the NT, CC, and CV systems which returned 14, 20, and 16 Mg ha^{-1} of vegetation, respectively. This higher input of organic matter to soil in the OR system can account for the higher soil C and N concentration than all other systems after 9 yr (Table 4). These higher levels of soil C and N were achieved despite the use of tillage (chisel plow and disk) for incorporating manure and of cultivation (low-residue sweep cultivator) for weed control.

Conventional no-tillage production systems have been shown to provide important benefits to long-term soil sustainability, in part by eliminating soil and C losses caused by tillage operations. Our results suggest that systems that incorporate high amounts of organic inputs from manure and cover crops can improve soils more than conventional no-tillage systems despite reliance on a minimum level of tillage. Our results suggest that, if adequate weed control could be achieved in reduced-tillage organic systems, they would be capable of providing improved soil quality with yield-enhancing benefits compared with conventional no-tillage systems. On the other hand, our results also suggest that, if conventional no-tillage systems utilized additional organic inputs or rotational perennial crops, they could probably achieve yield-enhancing soil quality benefits as well.

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